REMARKS

Claims 1-24 are currently pending in the above-identified patent application. In the subject Office Action the Examiner raised the question: "In a diffractive system where the diffraction grating is composed of the same transparent material as the substrate in which it is formed, is not the incident light also subject to refraction? The Examiner suggested that the term "refraction" be substituted for the language in claim 1: "a refractive surface," since the Examiner stated that the surface of the grating, which is comprised of a light-transmitting material, is still a refractive surface. Applicant wishes to thank the Examiner for having made this suggestion; in the zeroth order, a grating acts as a refractive surface. Claims 1, 15 and 20 have been amended to incorporate the Examiner's wording. No new matter has been added by this change.

Claims 15-24 were rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention, since the Examiner asserted that claim 15 recites the limitation "said photo responsive device" in lines 4-5 and 5-6, and there is insufficient antecedent basis for this limitation in the claim. The Examiner continued by suggesting that the phrase be changed to --said solar cell--. The same phrase also occurs in claim 20 at lines 4-5 and 5-6. Applicant again thanks the Examiner for the suggested change, and claims 15 and 20 have been amended to incorporate this wording. No new matter has been added by these changes.

Claims 1-3, 5, 6 and 8-13 were rejected under 35 U.S.C. 103(a) as being unpatentable over applicant's admissions of prior art in view of Czubatyj et al. (U.S. Pat. No. 4,419,533), since the Examiner asserted that in the present disclosure on page 7, lines 6-29 applicant admits that regarding claim 2, the device is a solar cell (p. 7, lines 22-23), regarding claim 3, the solar cell comprises silicon (p. 7, lines 26-27), regarding claims 6 and 8, the method of forming the gratings may comprise reactive ion etching (RIE) or wet chemical etching (p.7, lines 13-19), and regarding claim 9, the grating comprises rectangular projections (see Figure 2). The Examiner then stated that the method disclosed by the present application differs

from Czubatyj et al. because the method does not disclose the following:

a. The grating forms higher grating orders and a greater amount of incident light entering the device propagates more closely to the surface upon which the light is incident than is achieved by refraction, as recited in claim 1.

b. The device comprises silicon having a thickness of <100 pm, as recited in claim 5.

c. The grating comprises triangular projections, as recited in claim 10.

d. The grating comprises a blazed grating, as recited in claim 11.

e. The grating is chosen to have optimum performance within the solar spectrum, as recited in claim 12.

f. The method comprises the step of anti-reflection coating the surface of the grating upon which light is incident, as recited in claim 13.

Regarding claim 1, the Examiner stated further that Czubatyj et al. discloses a method for forming a grating solar cell comprising a transmission diffraction grating **178** on the light incident side of the solar cell **170**, wherein the transmission diffraction grating **178** is "arranged to direct all of the incident light through the intrinsic region **180** at an angle" (Col. 15, lines 38-51). The grating **178** is shown to be a sinusoidal diffraction grating, but it can also comprise any of the other disclosed gratings, such as a blazed grating, which is "preferred because the zero order reflections [transmissions in a transmissive grating], those normal to the grating, are minimized" (Col. 14, lines 47-53; and Col. 15, lines 49-51). The Examiner asserts that Czubatyj et al. also discloses, "designing a diffraction grating for higher order diffraction will provide greater angle to achieve internal reflection before this interface" (Col. 15, lines 34-37; see also Col. 6, lines 9-45).

The Examiner concluded that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the grating of the prior art method to use a diffraction grating that directs all the light at an angle, such as a blazed grating minimizing zero order diffraction, as taught by Czubatyj et al. because directing the light at an angle allows the longer wavelength light to be absorbed by the solar cell.

Regarding claim 5, the Examiner continued that Czubatyj et al. discloses using silicon to form the solar cell, wherein the solar cell comprises an n+ region having a thickness between 50 and 500 angstroms (0.005-0.050 μm), an intrinsic region having a thickness of about 4500 angstroms (0.45 μm) and a p+ region "as thin as possible" and having a thickness between 50 to 500 angstroms (0.005-0.050 μm) (col. 12, lines 22-55), and that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the solar cell of the prior art to be made of silicon and have a thickness of less than 100 μm as taught by Czubatyj et al. because silicon is a inexpensive and efficient material for converting sunlight into electrical energy.

Regarding claims 10 and 11, the blazed grating of Czubatyj et al. had triangular projections and minimizes zero order diffraction (Col. 14, lines 47-53). Claim 4 was rejected under 35 U.S.C. 103(a) as being unpatentable over applicants' admissions of prior art in view of Czubatyj et al. as applied above to claims 1,-3, 5, 6, and 8-13, and further in view of Mizuno et al., since the Examiner stated that the method of the disclosed prior art and Czubatyj et al. describe a method having the limitations recited in claims 1-3, 5, 6, and 8-11 of the instant invention as described above.

The Examiner stated that the method described by the prior art and Czubatyj et al. differs from the instant invention because they do not disclose the formation of a grating on both sides of the device, as recited in claim 4. However, Czubatyj et al. discloses gratings on both front and rear surfaces of the solar cell, but does not disclose an embodiment comprising two gratings at the same time. Mizuno et al. teaches that the diffraction grating can be adhered onto the front and back surfaces of thin film single crystal silicon and that light can be confined efficiently in the solar cells (Abstract). The Examiner concluded that it would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the method described by the prior art and by Czubatyj et al. to use a grating on the front and back surfaces to efficiently confine light in the solar cells.

The Examiner rejected claims 7, 14, and 15-24 under 35 U.S.C. 103(a) as being unpatentable over applicant's admission of prior art in view of Czubatyj et al.

in combination with other references. For the reasons to be set forth hereinbelow, applicant respectfully believes that Czubatyj et al. teaches away from the present invention. Applicant believes that the Examiner has improperly combined Czubatyj et al. with these references and with those set forth hereinabove, and therefore has failed to meet the burden of a *prima facie* case for an obviousness-type rejection.

Reexamination and reconsideration are respectfully requested.

Briefly, the present invention includes the application of a grating as a broadband long-wavelength absorption filter in a thick substrate of materials having an indirect band gap; that is, where the absorption is a strong function of wavelength, and where rear surface mirrors and multiple passes are not possible. Enhanced absorption is taught for long wavelengths, but not at the band edge. According to the present invention, the grating creates diffraction orders below the band gap that propagate at angles greater than $\theta_c = \sin^{-1}(1/n)$, where n is the refractive index of the substrate and θ_c is the critical angle for the material. The function of grating is to enhance the photovoltaic device performance through diffractive scattering beyond the angular cone defined by the total internal reflection angle, θ_c.

The mechanism responsible for this improvement is the increase in optical path length by the factor $2\cdot\sum[1/\cos(\theta_i)]$, where the summation is over all the transmitted diffraction orders propagating at angles θ_i; only ±1 orders are considered. Diffraction orders are generated whose directions of propagation θ_i are determined by the grating equation; depending on the angles θ_i, this number can be large, without a diffraction grating, this number is 1.

Turning now to the rejection of all claims under 35 U.S.C. 103(a) as being unpatentable over Czubatyj et al. in combination with other references, the teaching of the present claimed invention is at variance with the teachings of Czubatyj et al., where wavelengths below (shorter wavelengths) the band edge propagate at angles less than θ_c. This disagreement between the present invention and Czubatyj et al. follows from Czubatyj et al.'s application of gratings for absorption enhancement only at the band edge.

Although a direct comparison between Czubatyj et al. and the teachings of the present invention is difficult to make due to fundamental differences in physics and optics in their respective photovoltaic devices, in the following discussion applicant will demonstrate that the present invention operates poorly when the teachings of Czubatyj et al. are applied to the photovoltaic devices of the present invention. To begin, in Col. 15, lines 42-49, Czubatyj et al. states: "The incident light directing means **172** comprises a transmission diffraction grating **178** arranged to direct all of the incident light through the intrinsic region **180** at an angle. However, since nearly all of the shorter wavelength light will be absorbed in the intrinsic region **180** during the first pass, the diffraction grating **178** can be optimized for the longer wavelengths as previously described, while lines 60-62 of Col. 15 state: "The reflective metal layer **173** and TCO layer **175** form a back reflector to reflect unused light back into the intrinsic region **180**. Thus, Czubatyj et al. teaches the application of a grating as a narrow-band selective filter in a thin (~ 2 - 3 μm) film material having direct, band-gap absorption; that is, below the band edge, all wavelengths are absorbed within the thin-film structure in a single pass, while for longer wavelengths, the grating creates diffraction orders propagating at angles greater than $\theta_c = \sin^{-1}(1/n)$, where n is the refractive index of the thin semiconductor film, such that total internal reflection takes place at the semiconductor interfaces causing light confinement as a result of multiple passes through the film. Thus, Czubatyj et al. clearly does not describe the use of a grating in accordance with the teachings of the present invention which, in its simplest embodiment, does not require a reflective surface opposite the front surface grating and multiple reflections of the light to achieve improved utilization of the light.

Further, in Col. 15, lines 13-18 Czubatyj et al. states: "First order diffraction is also enhanced when d is about equal to a wavelength at the frequency of interest. Here, because most of the shorter wavelength photons are absorbed in the active intrinsic region **160** during their first pass, the longer wavelength photons of about 6600 Å and longer are of interest." Therefore, according to Czubatyj et al., the best first-order diffraction is achieved when the grating period is equal to the wavelength of interest. For amorphous silicon (Si) thin films, the band gap is at wavelength (λ)

of 0.66 μm, so the grating period (d) is chosen to be 0.66 μm. At normal incidence with $\lambda/d = 1$, and diffraction order $n = \pm 1$, the diffraction order angle is determined to be θ_c at normal incidence in their material system consisting of indium tin oxide ($n = 2.1$) and amorphous Si ($n = 3.5$). For all wavelengths below 0.66 μm, the diffraction orders propagate at angles less than θ_c, and will escape through the front surface after the first pass; however, since all shorter wavelengths are absorbed within the first pass, in the case of Czubatyj et al., this does not represent a loss mechanism.

Applying the teachings of Czubatyj et al. to the present invention, a grating period of 1.1 μm is selected to match the band edge at 1.1-μm for crystalline silicon photovoltaic devices as set forth in the present claimed invention. Assuming normal incidence on a transparent grating formed on a Si substrate having a refractive index of 3.5, for $\lambda = d = 1.1$ μm, the angles of the ± 1 transmitted orders are ± 16.6°. For shorter wavelengths; that is for λ = 1.0, 0.9, and 0.8 μm, as examples, the respective angles of ± 1 transmitted orders are ± 15.05°, ± 13.52 °, and ± 12.0°, respectively; all are less than the critical angle, θ_c. Therefore, for bending of light beyond θ_c, the grating behaves as if it were a planar surface, and a transparent front surface grating will not perform in accordance with the teachings of the present claimed invention; that is the selection of a grating period of 1.1 μm to match the band edge at 1.1 μm for the crystalline silicon photovoltaic devices taught by the present claimed invention does not result in the claimed transmitted orders having angles greater than the critical angle (independent claims 1, 15 and 20).

Figures 1 through 4, hereinbelow are graphs of the measured internal quantum efficiency (IQE) solar cells having gratings with periods between ~ 0.3 and 1.0 μm as a function of incident wavelength; otherwise, the gratings were fabricated in a similar fashion. To be noticed is: (1) The best long wavelength response is achieved at periods of ~ 0.5 μm and ~ 0.8 μm; (2) The worst long wavelength response is observed at periods of ~ 0.3 μm and ~ 1.0 μm; (3) The IQE enhancement for periods of ~ 0.5 μm and ~ 0.8 μm peaks at λ ~ 1.0 μm; and (4)

The IQE enhancement for periods of ~ 0.5 μm and ~ 0.8 μm peaks has a broad range varying from λ ~ 0.55 μm to λ ~ 1.15 μm.

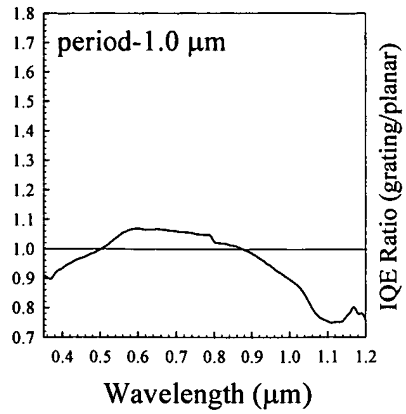

Figure 1. Internal Quantum Efficiency Ratio for Solar Cells having a Grating with ~ 1.0 μm Period.

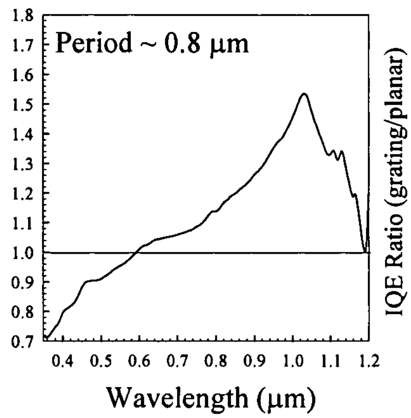

Figure 2. Internal Quantum Efficiency Ratio for Solar Cells having a Grating with ~ 0.8 μm Period.

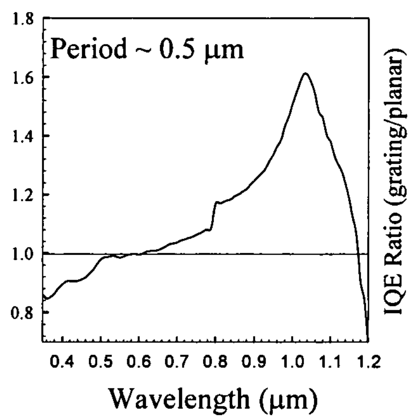

Figure 3. Internal Quantum Efficiency Ratio for Solar Cells having a Grating with ~ 0.5 μm Period.

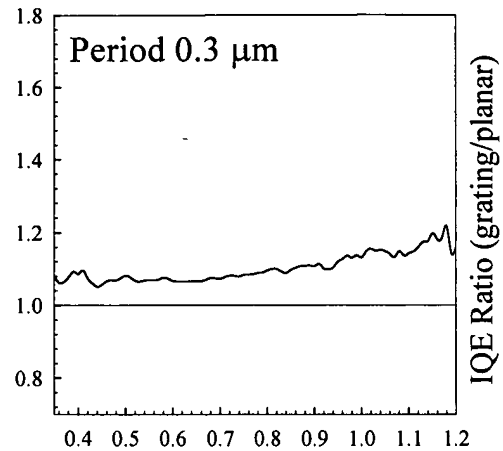

Figure 4. Internal Quantum Efficiency Ratio for Solar Cells having a Grating with ~ 0.3 μm Period.

The IQE enhancement for long wavelengths has been described in detail in the present Specification. Basically, for grating periods of 0.5 μm and 0.8 μm, the generated ±1, ±2, and ±3 diffraction orders propagate at angles greater than θ_c as shown in Tables 1 and 2 for normal incidence light.

Table 1: Diffraction Angle Distribution for a 0.5 μm Period.

Wavelength (μm)	First order diffraction Angles (±1)	Second Order diffraction Angles (±2)
0.8	27.2	66.1
0.9	30.95	> 90
1.0	34.85	> 90
1.1	38.9	> 90

Table 2: Diffraction Angle Distribution for a 0.8 μm Period.

Wavelength (μm)	First order diffraction Angles (±1)	Second Order diffraction Angles (±2)	Third Order diffraction Angles (±3)
0.8	16.6	34.85	59
0.9	18.75	40	74.64
1.0	20.93	45.58	> 90
1.1	23.13	51.77	> 90

The enhancement of the present invention in the long wavelength region can only be explained by diffractive scattering greater than the critical angle, θ_c. By creating many obliquely propagating diffraction orders, electron-hole pairs are generated closer to the front surface when compared with those for a refractive surface. By reducing bulk recombination losses, the IQE is enhanced.

This is unimportant according to the teachings of Czubatyj et al. since short wavelengths are absorbed within the same thickness due to the strong absorption of direct band gap structure. Therefore, using the grating teachings of Czubatyj et al. does not allow the present invention to perform as intended; rather, poor results are obtained for indirect band gap crystalline solar photovoltaic devices.

Moreover, although Czubatyj et al. teaches away from the use of crystalline silicon due to its poor optical absorption, it can be argued that that invention of Czubatyj et al. is not limited to amorphous silicon. As shown hereinabove, if one applies the teachings of Czubatyj et al. to a thin film crystalline configuration (grating period of 1.1 μm) optical losses increase and a poor photovoltaic device results due to the escape of shorter wavelengths.

For these reasons, applicant respectfully believes that the Czubatyj et al. reference teaches away from the subject claimed invention and, therefore, has been improperly combined with the references identified by the Examiner in the rejection of all pending claims under 35 U.S.C. 103(a). The Examiner has therefore failed to make a *prima facie* case for an obviousness-type rejection.

For the reasons set forth hereinabove, applicant believes that claims 1-24, as amended, are in condition for allowance and such action by the Examiner at an early date is earnestly solicited. Reexamination and reconsideration are respectfully requested.

Respectfully submitted,

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